ACT-12/96
CTP-TAMU-43/96
hep-ph/9608489

Theoretical Summary[a]

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After a quick tour through the present status of the Standard Model, an attempt is made to set up a framework to discuss some presently available exotica, including R_b and the CDF $ee\gamma\gamma + \not{E}_T$"event." Supersymmetry seems to be a key player in establishing a paradigm shift beyond the Standard Model.

1 Introduction

My task here is twofold: to summarize the theory talks given at this very exciting workshop *and* to provide some discussion on some theoretical aspects of supersymmetry, supergravity, and superstrings in a simplified way. Clearly, this seems virtually impossible, if it were not for the high quality and clarity of the talks we heard, and by the fact that supersymmetry has been one of the main experimental issues in this workshop. In the next section I will discuss some topics within the Standard Model, while in Section 3 I will provide some possible evidence/hints entailing an extension of the Standard Model. Section 4 is devoted to some characteristics of the Superworld, paving the way to some possible interpretations of presently existing exotica, such as R_b and the CDF $ee\gamma\gamma + \not{E}_T$"event", discussed in Section 5.

2 Standard Model Forever (?)

As we have repeatedly heard in this workshop, the Standard Model (SM) seems to be alive and in very good shape. More and more sectors of the SM get probed experimentally and still the results start to sound monotonous: no problem! From LEP1/1.5, to FNAL collider to HERA to ... all the data seem to be unanimously in favor of the SM. Sometimes one wonders what is so special about an $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory with three generations

[a]XI Topical Workshop on Proton-antiproton Collider Physics, Abano Terme (Padua), Italy, 26 May–1 June, 1996.

of quarks and leptons and spontaneous electroweak breaking (by the Higgs mechanism?) to describe nature so well. And to think that no theorist worth her soul wants it to be valid because of its numerous well-known defaults: too many parameters, no "real" unification, no gravity in sight, etc, etc. As Hollik[1] told us, the Electroweak (EW) precision observables, not only fit within the SM, but their sensitivity, through radiative corrections, to the mass of the Higgs boson, enables us to put an upper bound of $M_H \leq 300$ GeV at 95%CL. After the successful prediction of the top-quark mass[2], EW precision physics provides once more valuable information. While clearly EW precision data is the defining factor of the experimental worthiness of the Standard Model, all other information is in excellent agreement with the SM. As discussed here by Pilaftsis[3], the weak sector of the SM, related to the Cabibbo-Kobayashi-Maskawa (CKM) weak mixing matrix, including CP violation, seem to be in good phenomenological shape, amid the fact that we may not have as yet a universally acceptable theoretical explanation of the fermion mass spectrum, their mixings as well as of the origin of CP violation. Many of us believe that the "flavor problem" will find its solution at high energies/short distances, involving "new physics" beyond the Standard Model.

The status of CPT symmetry was also discussed here[3] rejecting, prematurely in my opinion, any possible framework that may lead to CPT violation. Since this is (or could be) a matter of the upmost importance, let me digress a bit. In point-like Quantum Field Theory one can prove, based on general principles like locality, Lorentz invariance, and unitarity, that CPT is always conserved, the well-known CPT theorem[4]. On the other hand, in Quantum Gravity one may see one or more of the above general principles not to hold, thus giving a chance to CPT violation. Specifically, in string theory, the only known framework for a consistent theory of Quantum Gravity, this possibility has been raised[5], and experimental efforts, mainly by the CPLEAR Collaboration[6], are reaching a very exciting range where some form of CPT violation may be observable. Namely, while the CPLEAR Collaboration determines that[6] $m_{K^0} - m_{\bar{K}^0}/m_{K^0} \leq 9 \times 10^{-19}$, naive quantum gravitation expectations lead one to believe that

$$\frac{m_{K^0} - m_{\bar{K}^0}}{m_{K^0}} \sim \frac{m_{K^0}}{M_{Pl}} \sim (10^{-18} - 10^{-19}) \tag{1}$$

with $M_{Pl} = (\sqrt{G_N})^{-1}$, with G_N the gravitational constant. It may be that these naive expectations, elaborated further and supported by some string calculations[5], are too optimistic and that the RHS of this equation is further suppressed, but stilll it is a very worthwhile effort and *we have to know* the best possible limits to CPT violation. After all, introducing an *arrow of time* in microscopic physics, is not a marginal issue.

The status of Quantum Chromodynamics (QCD) is not in bad shape either. For example, as discussed here by Mangano [7], rather elaborate perturbative QCD calculations, including resummation effects, take care of the bulk of the experimental data on jet physics, presented abundantly at this workshop. To my relief, the so called "CDF anomaly", referring to the CDF observation [8] that the high statistics inclusive jet production measurements at the Tevatron imply a larger cross section at high jet E_t than expected from NLO QCD calculations, seem to be accountable within the standard QCD framework [7,9,10]. Indeed, both the CDF and D0 inclusive jet cross sections are found to be in good agreement using a uniform theoretical NLO QCD calculation, taking into account the different kinematic coverages of the pseudo-rapidity variable (η) in the two experiments [9]. Subtle effects of jet algorithms, scale-choice and delicate cancellations amoung various contributions needed to be handled with extra care in the NLO QCD calculations, if precision down to the few percent level is required. Anyway, this is a very delicate analysis, still in progress, and we may have not yet heard the final verdict, but it looks like there is no need to call for "new physics" in order to explain the observed excess.

Further evidence for the validity of perturbative QCD calculations, including resummation effects, was presented by Berger [11], concerning this time the inclusive cross section for the production of top quark-antiquark ($t\bar{t}$) pairs in hadron reactions. A measure of the success of these calculations is the remarkable agreement between the theoretical predictions, worked out independently by three groups: (for $m_t = 175$ GeV and $\sqrt{s} = 1.8$ TeV)

$$\sigma_{t\bar{t}}^{\mathrm{th}}[\mathrm{pb}] = \begin{cases} 4.95^{+0.70}_{-0.40} & [12] \\ 5.52^{+0.07}_{-0.42} & [13] \\ 4.75^{+0.63}_{-0.68} & [14] \end{cases} \tag{2}$$

and the Tevatron measurements:

$$\sigma_{t\bar{t}}^{\mathrm{exp}}[\mathrm{pb}] = \begin{cases} 7.6^{+1.9}_{-1.5} & (\mathrm{CDF}) \quad [15] \\ 5.2 \pm 1.8 & (\mathrm{D0}) \quad [16] \end{cases} \tag{3}$$

On the non-perturbative QCD front, as we heard from Del Duca [17], quite remarkable progress has been made in trying to comprehend the vast amount of new data on diffraction, presented at this workshop. It looks to me that this is a very promising field of research, picking up momentum and maturing rapidly. Several other measurements at the Tevatron on different processes including W/Z production cross sections, W/Z+jets, Drell-Yan, W charge asymmetry, Z forward-backward asymmetry, double boson production, photon production, seem to fit nicely within the Standard Model.

All in all, the agreement between the present experimental status and the SM is rather remarkable and makes one wonder why we have to go ...

3 Beyond the Standard Model

There are many theoretical reasons indicating that an extension of the Standard Model is unavoidable. Non-inclusion of gravity in the unification program makes it incomplete. Here though, I would like to take a more pragmatic, close-to-the-experiment approach and argue that we have already experimentally strong hints that we have to enlarge the Standard Model. I am not referring here to the possible "exi(s)ting exotics" that may provide the first real cracks of the SM, as will be discussed below, but instead put together a convincing (?) case from within the Standard Model. What I am referring to here is to two *tentative* indications from precision (mainly LEP) data. The first one concerns the Higgs boson, that as we have heard here [1] (see also [2]) is probably "light" (≤ 300 GeV). Actually, a recent global fit [2], including all available data gives

$$M_H = 145^{+164}_{-77}\,\mathrm{GeV} \quad \text{and} \quad m_t = 172 \pm 6\,\mathrm{GeV} \tag{4}$$

a rather "light" Higgs boson indeed! While these are wonderful news for supersymmetric models, which generally predict

$$m_h^{\mathrm{susy}} \approx M_Z \pm 40\,\mathrm{GeV}\ , \tag{5}$$

it disfavors strongly-interacting Higgs scenarios, such as technicolor and the likes.

The second clue refers to the measured values of the three gauge coupling constants, indicating unification at a very high energy scale ($M_{\mathrm{LEP}} \approx 10^{16}$ GeV) and strongly favoring[18] supersymmetric GUTs, while excluding non-supersymmetric GUTs, which were already in deep trouble by the strict proton decay stability limits [19]. As a quantitative measure of the above statements we may use the predictions of GUTs and supersymmetric GUTs concerning $\sin^2\theta_W$ and confront them with the corresponding experimental value

$$\sin^2\theta_W|^{\mathrm{exp}}_{M_Z} \approx 0.232; \quad \sin^2\theta_W|^{\mathrm{nosusy}}_{M_Z} \approx 0.203; \quad \sin^2\theta_W|^{\mathrm{susy}}_{M_Z} \approx 0.230 \tag{6}$$

The numbers speak for themselves! One may want to add the successful prediction of the m_b/m_τ ratio and its straightforward implication of $N_\nu = 3$, [20] vindicated by LEP measurements, as further support for supersymmetric unification. Furthermore, the amazing success of the Standard Model severely constrains any attempt to extend it since new dynamical degrees of freedom may mess up its rather delicate structure. In this case too, supersymmetric

models manage to escape unscathed, in sharp contrast with dynamical symmetry breaking models, that as we have heard in this workshop, by De Curtis and Chiappetta [21] may have to just walk or limp or ...

So if we look at the score board, supersymmetric models do pretty well across-the-board, while dynamical symmetry breaking models leave too much to be desired. Thus, it is no accident or shouldn't be that surprising that the supersymmetric extension of the Standard Model has become the major framework for analyzing "new physics". In the late seventies, two major schools of thought were formed, one believed that "elementarity" of quarks, leptons, gauge bosons, etc continues all the way (or) close to the Planck length ($\ell_{Pl} \sim 10^{-33}$ cm), while the other school believed that "hell breaks loose" at the Fermi length ($\ell_F \sim 10^{-16}$ cm) and "elementarity" of at least some of the Standard Model particles has to be given up. I strongly believe that we have gathered enough evidence supporting the first point of view, , *i.e.*, the fundamental constituents of the Standard Model keep their "elementarity" up to very short distances, thanks to ...

4 The Superworld

Since the rudiments of supersymmetry (SUSY) have been discussed rather extensively in this workshop by our experimental colleagues while presenting discovery limits on different SUSY particles, I will concentrate here on some issues bearing direct consequences on the "exi(s)ting exotics" to be discussed in the next section. From a pragmatic/practical point of view, the role of supersymmetry may be effectively described as a *gauge hierarchy stabilizer*, thus leading to the following well-known relation

$$\widetilde{m}^2 \equiv m_B^2 - m_F^2 \approx \mathcal{O}(0.1 - 1\,\mathrm{TeV})^2 \tag{7}$$

where $\widetilde{m}$ represents the mass splitting between the fermion and boson in the same supermultiplet, i.e., it is a characteristic, generic, SUSY breaking scale, while the RHS represents the quantitative statement of the gauge hierarchy stability. It is because of this rather fundamental role of SUSY as a hierarchy stabilizer (7) that the hope exists for a whole new world, that of the superpartners of 'our world', to be within the discovery potential of presently available or soon to exist accelerators. A new issue then arises, that of the SUSY breaking mechanism, i.e., who provides the seeds for SUSY breaking and why is the SUSY breaking scale ($\widetilde{m}$) $\mathcal{O}(M_W)$? Before we move further, it is worth recalling that because the defining anticommutator of the SUSY generators ($\{Q, Q\} \propto P_\mu$) provides the four-momentum generator (P_μ), and since the latter is involved in General Relativity, we automatically get *local*

SUSY or *Supergravity*. The only way to break a local symmetry, consistently, is spontaneously, thus we are led to consider spontaneous SUSY breaking. The form and structure of supergravity interactions is such that spontaneous SUSY breaking is achievable in some sector of the theory, let us call it the *Hidden Sector* (H), and it is transmitted through the ubiquitous gravitational interactions, playing here the role of the *Messenger Sector* (M), to the *Observable Sector* (O) of the known quarks, leptons, gauge bosons, Higgs bosons, etc. [22]. Minimalistic applications of the above scenario routinely give

$$m_{3/2} \approx m_0 \approx m_{1/2} \approx \mathcal{O}(\widetilde{m}) \approx \mathcal{O}(0.1 - 1\,\mathrm{TeV}) \tag{8}$$

where $m_{3/2}$ is the mass of the gravitino, the spin-3/2 superpartner of the spin-2 graviton, while m_0 and $m_{1/2}$ are the *primordial* seeds of SUSY breaking in chiral multiplets (e.g., $q-\tilde{q}$, $\ell-\tilde{\ell}$, $h-\tilde{h}$, ...) and in gauge multiplets (e.g., $\gamma-\tilde{\gamma}$, $W-\widetilde{W}$, $Z-\widetilde{Z}$, $g-\tilde{g}$, ...) respectively. Usually m_0 and $m_{1/2}$ get renormalized through strong/electroweak interactions before they yield the experimentally measurable SUSY spectrum, generically represented here by $\widetilde{m}$. The gravitino, the gauge fermion of local SUSY, becomes massive by absorbing a spin-1/2 fermion, the *Goldstino*, through the super-Higgs mechanism, analogous to the usual Higgs mechanism of gauge theories. Phenomenologically, without asking too many questions at the microscopic level, such a generic picture as presented above, has met with considerable success in the following sense. It survived all the severe experimental tests, it succeeded to *reproduce* the Standard Model, without at the same time pushing SUSY masses to very high values, thus still experimentally observable, while *naturally* leading to gauge coupling unification 'observed' at LEP[18]. A characteristic experimental signature of SUSY has been missing E_T. Indeed, in the standard SUSY framework SUSY particles are produced always in pairs, and thus there is *always* a lightest supersymmetric particles (LSP), that is stable and escapes the detector. Usually the LSP is identified with the *neutralino* (χ_1^0), a linear combination of the electroweak neutral gauginos and the higgsinos[23]. The LSP is considered today as one of the main candidates for the Dark Matter (DM) of the Universe, as explained to us here by Turner [24]. Thus the experimental signature of SUSY, missing E_T, may be summarized as a *dark signal*.

While this minimalistic point of view has been quite successful in deriving phenomenologically viable SUSY models, it is characterized by several drawbacks. To start with, a gravitino mass in the mass range indicated in (8) and dictated by the resolution of the gauge hierarchy problem is just in the middle of the *cosmologically forbidden region*, causing unacceptable modifications to the primodial nucleosynthesis program[25,24]. Furthermore, while in the SUSY framework presented above it is possible to understand *dynamically*,

the electroweak breaking caused by SM radiative corrections and "derive" that $M_W \sim e^{-1/``\alpha"} M_{Pl}$, where "$\alpha$" is sone calculable function of gauge and top-quark Yukawa couplings [22], the correlation $\widetilde{m} \approx \mathcal{O}(M_W)$ remains a mystery, and looks like another hierarchy problem! In addition, one has to resort to *extraneous* fine-tuning to banish the cosmological constant (Λ_c) *even at the classical (tree) level*, while one has to fight hard the menace of SUSY FCNC [26], and of dimension-5 operators, endemic in SUSY theories, causing very fast proton decay [27], not unrelated with the fine-tuned way that the Higgs pentaplet gets split into a colored triplet and a weak doublet. While the above objections may look to the eyes of some experimentalists or hard phenomenologists as superfluous fine-printing, it looks to me like very important guiding principles, that may be able to navigate us to the right model. Let me remind you that the absence of FCNC in gauge theories, as exemplified by the tiny rate for $K_L \to \mu^+\mu^-$, while it looked of marginal importance to many, it did not so for Glashow, Iliopoulos, and Maiani, who tried to understand it naturally, thus introducing charm, and the rest is history.

There is a specific type of supergravity *no-scale supergravity* [22], that may hold the key to the solution of many of the above mentioned conundrums. It has been discovered by its defining property of providing *naturally*, without any fine-tuning, a vanishing cosmological constant Λ_c, at the classical level, *after* spontaneous SUSY breaking [28]. Furthermore, it has been used to *dynamically* determine, through SM radiative corrections, that $\widetilde{m} \approx \mathcal{O}(M_W)$, thus dynamically justifying (7) and thus completing the SUSY solution to the gauge hierarchy problem [29]. In addition, a large class of no-scale supergravity models [30], possessing a global, non-compact SU(N,1) symmetry, endemic in extended supergravities, is characterized by an *effective decoupling* of the local SUSY breaking scale from the global SUSY breaking scale. In other words, it is possible to have local SUSY breaking, while at the same time global SUSY is unbroken, thus in principle enabling us to drop the $m_{3/2}$ term from (8). More specifically, in this class of models one gets *dynamically* [30]

$$m_0 = A_0 = B_0 = 0 \tag{9}$$

where A_0 and B_0 refer to the Yukawa and Higgs SUSY breaking interaction terms. Thus, according to (8), the whole burden for global SUSY breaking is placed on $m_{1/2}$, and indeed very interesting models have been constructed realizing this picture. Actually, the *dynamically* derived universality (9) leads to an automatic resolution of the SUSY FCNC problem, since the squark and slepton masses are generated mainly through SM gauge couplings of the superpartners and thus are the same for, say $\tilde{u}$ and $\tilde{c}$, all proportional to the universal $m_{1/2}$! In other words, the down squark mass matrix is proportional

to the unit matrix and thus diagonal in any basis, including that one that diagonalizes the down quark mass matrix, thus enabling us to pass on the natural absence of FCNC in gauge theories to SUSY theories.

The effective decoupling between local and global SUSY breaking scales, as emerges naturally in no-scale supergravity, has led to a very entertaining possibility, namely that of a Very Light Gravitino (VLG) [31]. Indeed, in a certain class of no-scale models one can show that the following relation holds[31]

$$m_{3/2} \approx \left(\frac{m_{1/2}}{M}\right)^p M \tag{10}$$

where $M \approx 10^{18}\,\mathrm{GeV}$ is the appropriate gravitational scale. For $\frac{3}{2} \leq p \leq 2$ and $m_{1/2} \approx \mathcal{O}(100\,\mathrm{GeV})$ as it is dynamically determined, one gets

$$10^{-5}\,\mathrm{eV} \leq m_{3/2} \leq 1\,\mathrm{KeV} \tag{11}$$

a rather light gravitino indeed. Interestingly enough, the mass range (11) lies *outsise* the cosmologically forbidden region [25], thus there is no embarrassment in dealing with primordial nucleosynthesis. Another puzzle gets resolved. Nevertheless, such a very light gravitino has far-reaching experimental consequences, as first emphasized by Fayet [32]. In a nutshell, in interactions involving the gravitino, or more correctly its longitudinal spin-1/2 component the Goldstino, one has to replace the gravitational constant G_N by $G_N(\widetilde{m}/m_{3/2})^2$, thus effectively transmutting gravitational interactions into weak interactions for a large fraction of the mass range (11)! Such a gigantic enhancement of the gravitino interactions is bound to have a lot of experimental consequences. Interestingly enough, most of the mass range (11) is still phenomenologically admissible. The main characteristic of a VLG scenario is that undoubtedly, in this case, the gravitino is the LSP. As emphasized in [31], the neutralinos (χ_1^0) are unstable, decaying mainly to photons (γ) and the gravitino, with a lifetime proportional to $(m^5_{\chi_1^0}/(Mm_{3/2})^2)^{-1}$, thus depending on the gravitino mass, and offering the possibility of neutralino decay inside the detector. In such a case, the new experimental signature of VLG SUSY is γ's plus missing energy ($\not{E}_T$), in other words a *light signal*, in sharp constrast with minimalistic SUSY where we expect (as discussed above) a *dark signal*! In the case of VLG SUSY one has to resort to other particles (instead of the neutralino) to provide the dark matter in the universe, as discussed in this workshop [24].

It should be emphasized that the no-scale supergravity framework can accomodate any type of gravitino, from superheavy ($m_{3/2} \sim \mathcal{O}(M)$) [33], to minimalistic ($m_{3/2} \sim \mathcal{O}(M_W)$) [29,30], to very light ($m_{3/2} \sim (m_{1/2}/M)^p M$) [31], in each case providing a rather constrained, highly economical (in terms of

free parameters), and experimentally falsifiable model. While no-scale supergravity seems to resolve several of the drawbacks of the minimalistic viewpoint discussed above, due to its specific structure, the question has been frequently raised about the stability of the no-scale structure, when quantum corrections are taken into account. While *naively* the no-scale structure seems to collapse, we have retained for years the hope that such an amazing and rich structure should may perhaps be an exact property in the "right" quantum theory of gravity. Our hopes were not an illusion! Indeed, string theory, the only known consistent quantum theory of gravity, seems to yield as its long wavelength limit SU(N,1) no-scale supergravity, as first proven by Witten [34]. This "derivation" was valid in the weak coupling limit of string theory, thus once more the quantum stability of no-scale supergravity was in doubt. Lo and behold, during the last few months things have changed dramatically. String dualities, believed to be *exact* symmetries, have provided us with very powerful tools to map strongly-coupled string theories to weakly coupled ones. Specifically, the $E_8 \times E_8'$ heterotic string theory, which in its weak coupling yields [34] no-scale supergravity, has a strong coupling limit dual to the 11-dimensional long-wavelength limit of "M-theory", which has been very recently proven, by Banks and Dine [35] and Horava [36], to yield, within some controllable approximations, nothing else by no-scale supergravity! In other words, $E_8 \times E_8'$ heterotic string theory keeps, basically intact, the no-scale structure all the way from the weak coupling to the strong coupling limit, i.e., *including all quantum corrections*, to some controllable approximation. It does not take an heroic effort to dare to suggest that like string duality, the no-scale structure is an *exact* string property, far beyond the limits of perturbation theory that has been discovered, or "derived" in string theory, and thus eventually leading to a clear understanding of the natural vanishing of the cosmological constant (Λ_c) *exactly*, and not merely at the classical level.

Beyond high-brow theoretical consequences, these recent developments involving "M-theory" may have rather drastic and far-reaching phenomenological/experimental consequences, giving an unforseeable twist to the whole unification and SUSY model building program. Here is a micrography of what is going on. The 11th dimension, which becomes the 5th dimension after suitable compactification, seems to play a very peculiar and unheard before role. The extra 5th dimension, instead of being as usual periodic, it is a segment, [37] with the gauge and matter fields living at the endpoints only, while the supergravity and moduli fields propagate in the five-dimensional bulk! That is, spacetime is a narrow five-dimensional layer bounded by four-dimensional walls. At the one end "live" the "*observable fields*" (quarks, leptons, gauge bosons, etc.) coming from one of the E_8's, while at the other end "live" the "*hidden or shadow fields*"

contained in the other E_8. It is remarkable that when the coupling constants of the observable sector get their "normal values" (e.g., $\alpha_{\rm GUT} \sim 1/25$) the hidden sector ($E_8'$) coupling constant is driven to its strong limit, enabling it to form a gaugino condensate, a prerequisite for spontaneous local SUSY breaking. Actually, for distances ℓ between the "normal" 6-dimensional compactification radius R_{KK} (i.e., 10D$\rightarrow$4D) and the 5-dimensional compact radius R_5 (i.e., $R_{KK} \leq \ell \leq R_5$) even if the gaugino condensate has been formed, there is no local SUSY breaking. For distances $\ell > R_5$, local SUSY breaking occurs and clearly $m_{3/2} = f(R_5, ...)$, such that $m_{3/2} \rightarrow 0$ as $R_5 \rightarrow \infty$. Clearly, the 5th-dimension protects local SUSY, and the "geometrical picture" above is very suggestive and explains nicely the natural emergence of the no-scale structure in "M-theory".

It should not escape our attention the fact that the *scheme* discussed above: hidden$\rightarrow$messenger$\rightarrow$observable sector, for the transmission of SUSY breaking, is *literally* reproduced here. The one four-dimensional wall containing the E_8' is the *hidden sector*, the five-dimensional bulk with the supergravity, moduli fields is the *messenger sector*, and the other four-dimensional wall contains the *observable sector*. What is surprising is the fact that the onset of the fifth dimension leaves the observable sector intact. Gauge, Yukawa, and scalar interactions of the Standard Model are *oblivious* to the existence of the fifth dimension! This observation was made by Witten [38], who suggested that if the fifth dimension is suitably turned on below the unification scale ($M_{\rm LEP} \sim 10^{16}\,{\rm GeV}$), it may provide a kink in the gravitational coupling so that all couplings meet at $M_{\rm LEP} \sim 10^{16}\,{\rm GeV}$ (i.e., by $G_N E^2 \rightarrow G_N E^3 ...$), thus resolving the possible problem arising because of the disparity between $M_{\rm LEP}$ and the weak coupling string limit $M_{\rm string} \sim 5 \times 10^{17}\,{\rm GeV}$. Geometrical/topological decoupling between observable/supergravity/hidden fields in "M-theory" is suspiciously reminiscent of the decoupling that occurs naturally in SU(N,1) no-scale supergravity between local and global SUSY breaking, discussed above, and thus even if the "M-theory" is still in its infancy, it is not inconceivable that some formula similar to (9),(10) may eventually pop up from "M-theory". Further indirect evidence in support of such a viewpoint has been provided in Ref. [36], where it has been shown that the role of the would-be goldstino, to be absorbed by the gravitino in its way to becoming massive and thus breaking local SUSY, is played by the *normal component* of the 11-dimensional gravitino! In a way "M-theory" provides an effectively sealed, from the "observable sector", local SUSY breaking mechanism where all the ingredients are ingeniously provided by the 11th (eventually becoming the 5th) dimension.

It is amusing to notice that very early (pre string-theory) attempts [39] to

make sense out of D=11,N=1 supergravity theories suggested a gravitino mass of the form $m_{3/2} \sim (m_{1/2}/M)^2 M$, i.e., of the form given by (10) with $p = 2$! Actually, the 5-dimensional gravitational constant $G_N^{5-\mathrm{D}}$ seems to be much larger that the "normal" 4-dimensional one G_N, making one wonder whether the effective replacement in the case of VLG, of G_N by $G_N(\widetilde{m}/m_{3/2})^2$ discussed above, is somehow related (i.e., $G_N^{5-\mathrm{D}} = f[G_N(\widetilde{m}/m_{3/2})^2]$. To put it *bluntly*: is the VLG scenario the macroscopic "tip" of a microscopic "M-theory" 5th dimension? We don't know yet, but we are very likely going to know soon.

While we have tried to provide solutions to most of the drawbacks of the minimalistic SUSY framework, the puzzle of the dimension-five proton decay operator has not been dismissed. Actually, this problem gets worse if something like (9) is valid, because we do not have enough free parameters to play around, and specifically $m_0/m_{1/2} > \mathcal{O}(3)$ is required [40]. String theory comes once more to our rescue. For many well-known reasons [41], an SU(5)×U(1) unified gauge theory is most favored in string theory. The similarity to SU(2)×U(1) should be obvious, as the less known fact that this the *only known* string theory where fractional electric charges (e.g., ±1/2, etc.) get automatically confined in a way resembling $\mathrm{SU(3)_{color}}$ (QCD). [42]

The defining property of SU(5)×U(1) is that it reshuffles quarks and leptons in a **10** and $\bar{\mathbf{5}}$ in a way

$$\mathbf{10} = \left\{ \begin{pmatrix} u \\ d \end{pmatrix}, d^c, \nu^c \right\} \quad ; \bar{\mathbf{5}} = \left\{ u^c, \begin{pmatrix} \nu_e \\ e \end{pmatrix} \right\} \quad ; \mathbf{1} = e^c \tag{12}$$

different from SU(5)

$$\mathbf{10} = \left\{ \begin{pmatrix} u \\ d \end{pmatrix}, u^c, e^c \right\} \quad ; \bar{\mathbf{5}} = \left\{ d^c, \begin{pmatrix} \nu_e \\ e \end{pmatrix} \right\} \tag{13}$$

by *flipping* $u^c \leftrightarrow d^c$ and $e^c \leftrightarrow \nu^c$ and thus the reason some call SU(5)×U(1) *flipped* SU(5). By making the **10** contain an SU(3)×SU(2)×U(1) singlet (ν^c), it makes it useful (in the Higgs version) to break SU(5)×U(1) directly down to SU(3)×SU(2)×U(1), without the use of adjoint representations, thus getting the blessing of string theory. The structure (12) leads also to a natural Higgs-triplet-doublet splitting, resolving thus another minimalistic SUSY puzzle, while at the same time banishing the dangerous dimension-five proton-decay operators! Thus, we were led to consider [43] a stringy, no-scale, SU(5)×U(1) theory obeying (9), but still free of d=5 proton decay operators, either in its minimalistic form [43] (i.e., satisfying (8)) or in its VLG form [44] (i.e., satisfying (10)). In order to find out which way nature prefers if any in the rather broad framework developed in this section, we have to pay some due attention to the presently available ...

5 Exi(s)ting Exotics

Most of the experimental and theoretical talks in this workshop finished with the, by now, expected words to the effect "we have seen nothing unusual or unexplainable by the Standard Model ...". Fortunately there are two very noticeable exceptions, that of R_b and the CDF $ee\gamma\gamma + \not{E}_T$ "event". Let me discuss each of these in turn.

5.1 R_b

It is by now well-known that if we define $R_Q \equiv \Gamma(Z^0 \to Q\bar{Q})/\Gamma(Z^0 \to \text{hadrons})$, then we have the following theoretical(SM)- experimental mismatch for R_b and R_c:

$$R_b^{\text{exp}} = \begin{cases} 0.2202 \pm 0.0016, & \text{for } R_c^{\text{SM}} = 0.172 \\ 0.2211 \pm 0.0016, & \text{for } R_c \text{ "free"} \end{cases} \tag{14}$$

while $R_b^{\text{SM}} = 0.2157$, and

$$R_c^{\text{exp}} = 0.160 \pm 0.007 \tag{15}$$

while $R_c^{\text{SM}} = 0.172$.

What is even more peculiar is the fact that the leptonic Z-widths (Γ_{lep}) and the *total* hadronic Z-width (Γ_{had}) seem to be in very good agreement with the SM ($|\Delta\Gamma_{\text{had}}| < 3\,\text{MeV}$). One of course may take the attitude that $R_{b,c}^{exp}$ are just some experimental flukes/fluctuations and they will eventually "relax" to their SM values. Something perhaps already happening, with at least R_c^{exp}! On the other hand, as discussed in considerable detail by Feruglio [10], we can use the so-called "$R_{b,c}$-crisis" to see how well we are doing with the extensions of the SM discussed in the previous sections. The first thing that comes to mind is of course SUSY contributions. Indeed, it has been suggested [45] that SUSY loop corrections to the $Z - b - \bar{b}$ vertex involving "light" charginos ($\chi_1^\pm$) and top squarks ($\tilde{t}$) may provide a ΔR_b^{susy} such as to close the gap between theory and experiment, as indicated in (14). While at first sight this statement sounds plausible, things get a bit more complicated. If we take into account *all* available constraints from: LEP 1.5 limits on chargino ($m_{\chi_1^\pm} > 65\,\text{GeV}$ if $m_{\chi_1^\pm} - m_{\chi_1^0} > 10\,\text{GeV}$) and top-squark ($m_{\tilde{t}}$) masses, limits from D0 on chargino masses, limits on Higgs boson masses, etc, and run 365,000 SUSY models (for $1 < \tan\beta \equiv \frac{v_2}{v_1} < 5$) and other 91,000 SUSY models (for $1 < \tan\beta < 1.5$) one finds [46]

$$\Delta R_b^{\text{susy}} \leq 0.0017\ , \tag{16}$$

not big enough to fill in the gap in (14). There are some recent claims [47] that the upper bound (16) may be avoided in certain very restrictive regions of parameter space that require a severe fine-tuning of the parameters in the top-squark mass matrix. If then SUSY contributions cannot make up the difference, what else is there to fix up R_b? As explained in [10], the existence of an extra light neutral gauge boson Z', coupled *only* to quarks, and *not* to leptons, thus *leptophobic* [48], and with the right mixing with the regular Z, can do the job. A leptophobic Z' does not upset $\Gamma_{\rm lep}$, while by its appropriate mixing (θ) with the regular Z it may be made phenomenologically consistent with the SM, including $\Gamma_{\rm had}$. Actually, detailed fits to the electroweak data [48,49,50] allow values for the parameter $\delta \equiv \theta g_{Z'}/g_Z$ as large as 10^{-2}. Even if an appropriate Z' may fit $R_b^{\rm exp}$, the standard question arises: "who asked for that?" Put it in a different way, if such a Z' explanation is to be taken seriously, one must provide a consistent theoretical framework where the new gauge boson and its required properties arise naturally. Since a most important theoretical issue, that of cancellation of gauge anomalies involving Z', is dealt with *automatically* in the string framework developed in the previous section, there is where we have to look. New light neutral gauge bosons (Z') were early on considered to be the "smoking guns" of string, back when $E_6(\subset E_8)$ was the favorable, string-inspired gauge group [51]. It has been shown recently [48] that *dynamic leptophobia* is possible via RGE U(1) mixing, and specifically the so-called η-model [52] in (string-inspired) E_6 stands out as the most reasonable model that fits all the SM constraints and $R_b^{\rm exp}$. One may wonder if a more natural way to achieve leptophobia exists, namely *symmetry-based leptophobia*. Actually, we don't have to wonder very far since SU(5)×U(1) does the job [53]. Let me remind you that generically in string theory, your "chosen" (or "preferred") gauge group is *unavoidably* accompanied by extra U(1) factors. Sometimes it may be that the extra U(1)'s are broken at the string scale, thus useless for providing light Z's. Nevertheless, it may happen that one extra U(1) survives unbroken down to low energies, and if we are lucky, it may even fit the bill. Indeed, we managed [53] to arrange our "preferred" SU(5)×U(1) model to be accompanied by an extra U(1) surviving to low energies. What it rather stunning is that leptophobia is very natural in SU(5)×U(1). The reason is very simple. A look at the way that quarks and leptons are distributed in the **10** and $\bar{\mathbf{5}}$ of SU(5)×U(1), see (12), makes it clear the fact that the **10** contains *only* quarks (the ν^c is superheavy), and the $\bar{\mathbf{5}}$ mixes quarks and leptons. Thus, it is very easy to imagine a scheme where some Z' couples only to **10**'s and not the $\bar{\mathbf{5}}$'s, thus "leptophobic" because of symmetry reasons! Notice that we cannot pull the same trick for "canonical" SU(5) because, as is apparent from (13), both **10** and $\bar{\mathbf{5}}$ mix quarks and leptons. String-based Z' charge assignments lead to

scenarios where R_b is shifted significantly in the direction indicated experimentally, while keeping $\Gamma_{\rm had}$ essentially unchanged and producing much smaller shifts for R_c [53]. It is worth mentioning that, while the specific Z' couplings to quarks may change for different string realizations of SU(5)×U(1), there are certain phenomenological characteristics that reflect the endemic SU(5)×U(1) leptophobia, as quarks are largely split from leptons in the SU(5) representations. Namely, maximal parity-violating couplings to up-type quarks and parity-conserving couplings to down-type quarks, that have the potential of yielding observable spin asymmetries in polarized pp scattering at RHIC [54]. The present experimental status of Z' gauge bosons was discussed here by Eppley and Wenzel [55]. For a detailed phenomenological study of SU(5)×U(1) Z' bosons, including production cross sections, additional contributions to the top-quark cross section, and spin asymmetries at RHIC, see [53]. It is very important to realize that even if Z-Z' mixing *is not found* to be the resolution of the R_b puzzle, leptophobic Z' gauge bosons may still be predicted by string models (unmixed or negligibly mixed with the Z') and their existence should be probed experimentally in *all* possible ways. It is worth emphasizing that even if the "$R_{b,c}$-crisis" gets resolved purely experimentally, something that looks, at least to me not inconceivable, the would-be "agreement" between $R_{b,c}^{\rm SM}$ and $R_{b,c}^{\rm exp}$ would put severe constraints on possible extensions of the SM. In other words, the "imagination stretch" now triggered by $R_{b,c}^{\rm exp}$ wouldn't have been futile, because now "all chips are down", e.g., (16), or possible existence of leptophobic Z' that can be probed experimentally in the near future.

5.2 *The CDF $ee\gamma\gamma + \not{E}_T$ "event"*

As we heard from Carithers [56], and further discussed in [10], recent observations at the Tevatron, in the form of a puzzling $ee\gamma\gamma + \not{E}_T$ event [57], appear to indicate that experiment may have finally reach the sensitivity required to observe the first *direct* manifestation of supersymmetry [58,59,44]. If this event is indeed the result of an underlying supersymmetric production process, as might be deduced from the observation of additional related events at the Tevatron or LEP 2, then indeed we would have crossed a new threshold, literally and methaphorically, in elementary particle physics. The particulars of the event are listed in Table 1. The direct evidence for supersymmetry contains the standard missing-energy characteristic of supersymmetric production processes, but it also contains a surprising *hard-photon* component (as far as minimalistic SUSY is concerned), which eliminates all conceivable Standard Model backgrounds (e.g., if $WW\gamma\gamma$ is the origin of the "event", less than 10^{-3} events are expected with the current CDF data) and may prove extremely dis-

Table 1: The kinematical information of the observed CDF $ee\gamma\gamma + \not{E}_T$ event. All momenta and energies in GeV. Also important are $\not{E}_T = 52.81\,\text{GeV}$ at $\phi = 2.91\,\text{rad}$.

Variable	e_1	e_2	γ_1	γ_2
p_x	58.75	-33.41	-12.98	31.53
p_y	18.44	11.13	-29.68	-17.48
p_z	-167.24	21.00	-22.69	-34.77
E	178.21	41.00	39.55	50.09
E_T	61.58	35.21	32.39	36.05

criminating among different models of low-energy supersymmetry. The present supersymmetric explanations of the CDF event fall into two phenomenological classes: either the lightest neutralino (χ_1^0) is the lightest supersymmetric particle, and the second-to-lightest neutralino decays radiatively to it at the one-loop level ($\chi_2^0 \to \chi_1^0\gamma$) [59]; or the gravitino ($\widetilde{G}$) is the lightest supersymmetric particle, and the lightest neutralino decays radiatively to it at the tree level ($\chi_1^0 \to \widetilde{G}\gamma$) [58,59,44,60]. These two explanations fall respectively into the "minimalistic SUSY" framework and the Very Light Gravitino (VLG) framework, discussed in Section 4. The former "neutralino-LSP" scenario requires [59] a configuration of gaugino masses that precludes the usual gaugino mass unification relation of unified models, although it can occur in some restricted region of the "minimalistic SUSY" parameter space. The latter "gravitino-LSP" scenario requires only that the lightest neutralino has a photino component, as is generically the case. The underlying process that leads to such final states has been suggested to be that of selectron pair-production ($q\bar{q} \to \widetilde{e}^+\widetilde{e}^-$, $\widetilde{e} = \widetilde{e}_R, \widetilde{e}_L$), with subsequent decay $\widetilde{e} \to e\chi_2^0$ or $\widetilde{e} \to e\chi_1^0$ in the "neutralino-LSP" and "gravitino-LSP" scenarios respectively. In the "gravitino-LSP" scenario, the alternative possibility of *chargino pair-production* ($q\bar{q} \to \chi_1^+\chi_1^-, \chi_1^\pm \to e^\pm\nu_e\chi_1^0$) has also been suggested [60].

Theoretically, the "gravitino-LSP" explanation, belonging to the VLG framework (see Section 4), is much more exciting and has generated model-building efforts that try to embed such a scenario into a more fundamental theory at higher mass scales. These more predictive theories include low-energy gauge-mediated dynamical supersymmetry breaking [58,61] and no-scale supergravity [44]. In the former case (super)gravity seems to play a rather minuscule role in the low-energy world, by essentially putting all the burden of SUSY breaking into gauge (old or new) interactions. This sounds a little bizarre, as one of the striking consequences of the VLG framework, as discussed in Section 4, is the immense enhancement of the gravitational constant ($G_N \to G_N(\widetilde{m}/m_{3/2})^2$), in processes involving the would-be goldstino, pushing

it up to at least the Fermi constant ($G_F \sim 10^{-5} m^2_{\rm proton}$)! On the other hand, in the latter case, that of no-scale supergravity [44,60], as discussed in the previous section, (super)gravity plays a rather drastic role in the low-energy world, and the aformentioned enhancement of the gravitational constant is used to provide a *window of opportunity* to probe very high mass scales/very short distances, including the exciting possibility of the unfolding of a fifth-space dimension! As such, I will concentrate henceforth in the no-scale supergravity interpretation [44,60], since furthermore, the low-energy gauge-mediated dynamical SUSY breaking has been covered in [10].

The alert reader may have already noticed that the CDF "event" is a striking example of the VLG signature: γ's plus missing energy (E_T), as contained in the VLG one-parameter no-scale supergravity [44], that was developed in Section 4. Here is our strategy. We delineated the regions in parameter space that are consistent with the experimental kinematical information (see Table 1), and then we consider the rates for the various underlying processes that may occur within such regions of parameter space. We also consider the constraints from LEP 1.5 and the prospects for SUSY particle detection at LEP161 and LEP190. The rather restrictive nature of our one-parameter model make our experimental predictions unambiguous and highly correlated. Here are our results.

(A) Selectron interpretation

The underlying process is $q\bar{q} \to \widetilde{e}^+_R \widetilde{e}^-_R$ or $q\bar{q} \to \widetilde{e}^+_L \widetilde{e}^-_L$, with subsequent selectron decay via $\widetilde{e}^\pm_{R,L} \to e^\pm \chi^0_1$ with 100% B.R., followed by neutralinos decaying via $\chi^0_1 \to \gamma \widetilde{G}$, also with 100% B.R. The final state thus contains $e^+e^-\gamma\gamma\widetilde{G}\widetilde{G}$, with the (essentially) massless gravitinos carrying away the missing energy. We found that in our model [44,60] $\widetilde{e}_L$ production is disfavored, while $\widetilde{e}_R$ is perfectly consistent with the kinematics of the event, with

$$m_{\tilde{e}_R} \approx (85 - 135)\,\mathrm{GeV}\,,\, m_{\chi^0_1} \approx (50 - 100)\,\mathrm{GeV} \text{ implying } m_{\chi^\pm_1} \approx (90 - 190)\,\mathrm{GeV} \tag{17}$$

The specific microprocesses in the selectron interpretation are

$$\begin{aligned} q\bar{q} &\to \gamma, Z \to \widetilde{\ell}^+_R \widetilde{\ell}^-_R, \widetilde{\ell}^+_L \widetilde{\ell}^-_L \to (\ell^+ \chi^0_1)(\ell^- \chi^0_1) \to \ell^+\ell^-\gamma\gamma + \not{E}_T \\ q\bar{q}' &\to W^\pm \to \widetilde{\ell}^\pm_L \widetilde{\nu}_\ell \to (\ell^\pm \chi^0_1)(\nu_\ell \chi^0_1) \to \ell^\pm \gamma\gamma + \not{E}_T\,, \\ q\bar{q} &\to Z \to \widetilde{\nu}_\ell \widetilde{\nu}_\ell \to (\nu_\ell \chi^0_1)(\nu_\ell \chi^0_1) \to \gamma\gamma + \not{E}_T\,, \end{aligned} \tag{18}$$

where $\ell = e, \mu, \tau$. Our calculations indicate [60] that at the *one* dilepton-event level, the expected number of *single*-lepton events (two) or *no*-lepton (diphoton) events (negligible) is still consistent with observation (zero). However,

possible observation of more $ee\gamma\gamma + \not\!\!E_T$ events would need to be accompanied by many more $e\gamma\gamma + \not\!\!E_T$ or $\gamma\gamma + \not\!\!E_T$ events.

(B) Chargino interpretation

The underlying process is assumed to be $q\bar{q} \to \chi_1^+\chi_1^-$, with subsequent chargino decay via $\chi_1^\pm \to e^\pm \nu_e \chi_1^0$ (with a calculable B.R.), followed by the usual neutralino decay $\chi_1^0 \to \gamma\widetilde{G}$. The final state thus contains $e^+e^-\gamma\gamma\nu_e\bar{\nu}_e\widetilde{G}\widetilde{G}$, with the (essentially) massless gravitinos and the neutrinos carrying away the missing energy. A similar analysis as above (A) shows that in this case one predicts comparable rates (to the $ee\gamma\gamma + \not\!\!E_T$ event) for $(\ell^\pm\ell'^+\ell'^-, \ell^+\ell^-, \ell^+\ell^- jj)\,\gamma\gamma + \not\!\!E_T$. In this interpretation it would be reasonable to require $100\,\mathrm{GeV} < m_{\chi_1^\pm} < 150\,\mathrm{GeV}$ (which implies $m_{\tilde{e}_R} > 85\,\mathrm{GeV}$ and $m_{\chi_1^0} > 55\,\mathrm{GeV}$).

In the VLG–no-scale supergravity[44,60] interpretation (selectron or chargino) of the CDF "event", both selectrons and charginos (with masses in the $\mathcal{O}(100\,\mathrm{GeV})$ region) seem to be kinematically inaccessible at any LEP2 energy presently being considered (i.e., $\sqrt{s} = 161, 175, 190$ GeV). One then has to focus on the $\chi_1^0\chi_1^0$ and perhaps also $\chi_1^0\chi_2^0$, as the only observable channels. In either case an acoplanar photon pair plus missing energy ($\gamma\gamma + \not\!\!E_T$) final state, constitutes a rather clean signal. The "non-observation" of these events at LEP 1.5 does not exclude any region of parameter space. It is worth mentioning that we have pointed out [60] that one of the acoplanar photon pairs observed by the OPAL Collaboration [62] at LEP 1.5 may be attributable to supersymmetry in the VLG–no-scale supergravity [44,60] model via $e^+e^- \to \chi_1^0\chi_1^0 \to \gamma\gamma + \not\!\!E_T$! Needless to say that we eagerly expect the completion of the analyses of the current LEP run ($\sqrt{s} = 161$ GeV).

It goes without saying that the consequences of confirming the supersymmetry origin of the CDF "event" will be rather dramatic. In at least one interpretation it would not only provide evidence for a fundamental new symmetry of Nature (supersymmetry), but it would also connect us directly, through a fifth space dimension, to Planck-scale physics. On the other hand, it may be that the CDF event is some sort of fluctuation/glitch/or whatever... Hopefully, by the next workshop (XII) in this series, next year, we will know.

Acknowledgments

It is a great pleasure to thank Luca Stanco and the other members of the organizing committee for inviting me to give this summary talk, for their warm hospitality, and for putting together a very exciting conference, that among

other things triggered my real interest in the CDF "event". My thanks are also due to Jorge Lopez for discussions and reading the manuscript. This work has been supported in part by DOE grant DE-FG05-91-ER-40633.

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